Title
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Journal
Journal of Applied Ecology, 57(1)

ISSN
0021-8901

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Publication Date
2020

DOI
10.1111/1365-2664.13521

Peer reviewed

Received: 16 May 2019 | Accepted: 9 September 2019

DOI: 10.1111/1365-2664.13521

POLICY DIRECTION

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

Emerging risks of non-native species escapes from aquaculture: Call for policy improvements in China and other developing countries

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Funding information
National Key Research and Development Program of China, Grant/Award Number: 2017YFC1200100 and 2018YFC1406402; National Natural Science Foundation of China, Grant/Award Number: 31670544; Project of Science and Technology Commission of Shanghai, Grant/Award Number: 18DZ1206507

Handling Editor: Sarah Knutie

Abstract

1. Global aquaculture relies heavily on the farming of non-native aquatic species (hereafter, NAS). NAS escapes from aquaculture facilities can result in serious aquatic bio-invasions, which has been an important issue in the FAO *Blue Growth Initiative*. A regulatory quagmire regarding NAS farming and escapes, however, exists in most developing countries.
2. We discuss aquaculture expansion and NAS escapes, illustrate emerging risks and propose recommendations for improved aquaculture management across developing countries and particularly for China.
3. In China, 68 NAS are known to have successfully established feral populations in natural habitats due to recurrent leakages or escapes; among the 68 NAS, 52 represent risks to native aquatic ecosystems. In addition to affecting a country's own biodiversity and ecosystem functions, NAS escapees can also threaten the biosecurity of shared waters in neighbouring countries.
4. *Policy implications*. Non-native aquatic species (NAS) escapes have already had adverse ecological effects in China and other developing countries. The importance of this problem, however, is not adequately recognized by current conservation policies in developing countries. To conserve biodiversity and to support the goal of FAO's sustainable aquaculture, developing countries should now take responsible actions to address NAS escapes through policy and management improvements. Specifically, these countries should pass comprehensive legislation, establish effective agencies and national standards and planning and enhance integrated research and education to deal with risk assessment, prevention, monitoring and control of NAS escapes. Given that China is the world's largest aquacultural producer, China can create a model for other developing countries that will increase the biosecurity and sustainability of global aquaculture.

KEYWORDS
aquaculture, aquatic species, biological diversity, biological invasion, conservation policy, domestic species, exotic species, non-native aquatic species

Rui-Ting Ju and Xiao Li contributed equally to this work.

1 | INTRODUCTION

Aquaculture—the farming of fish, mollusks, crustaceans and aquatic plants—is the fastest growing sector of the world food industry (FAO, 2016). This rapid growth relies heavily on the introduction of exotic species or domestic species outside of their natural ranges (hereafter, non-native aquatic species, NAS); a total of 5,612 records of NAS introduction have been collected by the FAO (2019). The farming of non-native fishes, for example, contributes 17% to global aquaculture production (FAO, 2012). In many developing countries, e.g., India, Philippines, Cuba and Brazil, aquaculture predominantly depends on the farming of NAS; yields of NAS represent 60%–95% of aquatic food production in those countries (Shelton & Rothbard, 2006). This situation is greatly affecting global environments, economies and even sociocultural arrangements (Lima-Junior et al., 2018; Lövei & Lewinsohn, 2012; Pelicice, Vitule, Lima-Junior, Orsi, & Agostinho, 2014).

The escape of NAS from aquaculture facilities has become a serious global problem (FAO, 2016). Although it is difficult to accurately assess the number and magnitude of escapes due to limited statistics, the trend is worrying because many escapes are known to have occurred world-wide (e.g. Thorvaldsen, Holmen, & Moe, 2015; Toledo-Guedes, Sanchez-Jerez, Benjumea, & Brito, 2014) and especially in developing countries (Gao et al., 2017; Sepúlveda, Arismendi, Soto, Jara, & Faria, 2013). In addition to economic loss, the escape of farmed NAS can generate multiple ecological outcomes. Not unlike invaders of terrestrial ecosystems, the escapees from aquaculture have resulted in aquatic bio-invasions that reduce the biodiversity and affect ecological functions of native ecosystems (Vitule, Freire, & Simberloff, 2009). The International Union for Conservation of Nature (IUCN) cites the impacts as 'immense, insidious, and usually irreversible' (IUCN, 2000). In the new framework of the *Blue Growth Initiative* issued by the FAO, NAS escapes and invasions are considered among the most important issues facing the global aquaculture industry (FAO, 2016).

In this paper, we briefly discuss aquaculture expansion and NAS escapes, illustrate emerging risks and propose a set of recommendations for aquaculture governance and management for developing countries. Although this topic has also been reviewed elsewhere (e.g. Lin, Gao, & Zhan, 2015; Pelicice et al., 2014), the policy direction for NAS management seems insufficiently clear and comprehensive. We focus here on NAS used for aquaculture and especially on those NAS that have escaped from aquaculture facilities. In addition, we mainly focus on China, which leads the world in aquaculture output and in NAS escapes. Because China's experiences and problems with NAS are not unique, it is hoped that the solutions recommended here can be also helpful to other developing countries.

2 | EXPANSION AND ESCAPES IN AQUACULTURE

Global aquaculture has been rapidly increasing over the past five decades, with a doubling time of less than 10 years (Figure 1), and developing countries have contributed greatly to this rapid growth (FAO, 2016). China has been paralleling and dominating the global trend since the 1990s (Figure 1). In 2016, China accounted for 58% (63.7 million tons) of the global aquaculture volume and 63% (US$ 153.4 billion) of the global aquaculture value, making China the world's largest aquaculture producer (FAO, 2016). China's output of farmed NAS is also the largest in the world and represents more than 25% of the country's total aquaculture production (FAO, 2016; Shelton & Rothbard, 2006). These NAS include 252 species, which are mainly fish, mollusks, algae and crustaceans (see tables 1 and 2 in Lin et al., 2015). The most dominant species are the Nile tilapia *Oreochromis niloticus*, the channel catfish *Ictalurus punctatus* and several sturgeon species (*Acipenser* spp., *Huso huso* and *Polyodon spathula*), which contribute respectively 65%, 40% and 85% to the global production of these groups (Lin et al., 2015). Most of China's farmed NAS result from international introductions. Although the number of domestic transferred species is relatively small, their introduction frequency is high (Xiong, Sui, Liang, & Chen, 2015).

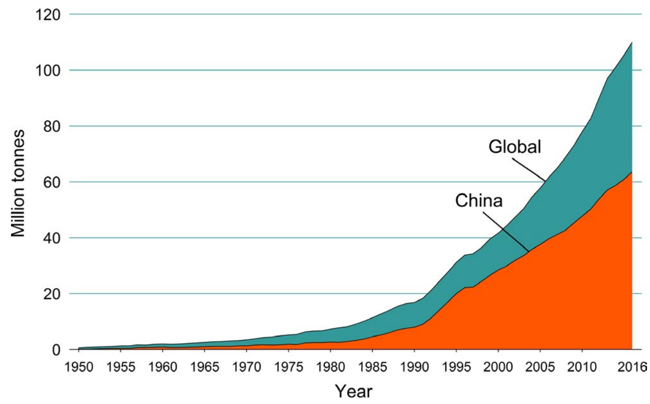

FIGURE 1 World aquaculture production of aquatic animals and plants (1950–2016). Data from FAO (2018)

Like many other developing countries (e.g. Vietnam, Chile and Thailand) (Kernan, 2015), China's aquaculture industry is quite vulnerable to extreme weather. Since 2005, typhoons and floods have destroyed 6.4 million hectares of aquaculture facilities and have caused more than 8.4 million tonnes of loss in aquaculture production in China (see Figure S1); these losses have been associated with mass escapes of farmed NAS (Gao et al., 2017). Most escape events occur in southern China, which is the major NAS production region in the world (Xiong et al., 2015). Although the loss of fishery production during escape events is a serious problem, an even more serious problem is the possibility of biological invasion, i.e., the possibility that NAS become established in the wild and adversely affect native biodiversity and ecosystems. In China, more than 100 farmed NAS have escaped and entered natural waters (Xiong et al., 2015). In our view, the importance of the problem of NAS escapes has not been matched by the level of official oversight in China or in other developing countries.

3 | EMERGING RISKS

Although many non-native species fail to establish in the wild if they lack sufficient propagule pressure (Simberloff, 2009), NAS that escape from artificial facilities have posed high risks to native aquatic ecosystems in China and beyond. About 68 NAS are known to have successfully established feral populations in China's natural habitats as a result of recurrent leakages or escapes (see Table S1), but this number is likely to rise substantially in the future. The extremely diverse habitats over the vast >18,000 km of coastline and 175,000 km^2 of inland water bodies in the country can probably support almost all NAS. Among those 68 NAS that have established feral populations, 52 are thought to have potential effects on native ecosystems in China (Table S1); for nearly 80% of the total farmed NAS (252 species), risks associated with their escape are unexplored. Given that human activities under globalization and the ongoing '*the Belt and Road*' initiated by China will likely increase the transfer of NAS among countries, and given that the frequency and intensity of extreme weather events are projected to increase under climate change, risks of NAS escape and invasion world-wide are likely to increase in the future (Wu & Ding, 2019). Because China and several neighbouring countries are connected by water areas, the escaped NAS can also affect aquatic ecosystems in other developing countries. In particular, many neighbours (e.g. Myanmar, Thailand and Cambodia) are located in global biodiversity hotspots, and the risks posed by escaped NAS to these neighbours require attention; shared rivers, such as the Mekong River, are of special concern (Kang et al., 2009).

Non-native aquatic species escapes can cause biodiversity loss, ecosystem degradation and even endemic species extinction through both direct competition or predation and indirect trophic cascades. These effects often occur in both developed and developing countries (e.g. Lima-Junior et al., 2018; Naylor, Williams, & Strong, 2001). Similar direct and indirect effects are possible for the 65% of the NAS (44 species) that have established feral populations in China (Table S1). These effects mainly result from intentional introductions of NAS, careless operations or extreme weather, as discussed earlier.

Farmed NAS also carry uninvited 'hitch-hikers', which have been a troublesome problem for the global aquaculture industry (FAO, 2016). Such hitch-hikers include free-living invertebrates, parasites, pathogens and fouling species; in addition to affecting the aquaculture industry itself, these hitch-hikers, if they escape from aquaculture facilities, can enter new water bodies and harm wild species and ecosystems. Seven NAS that carry hitch-hikers are known in China's aquaculture (Table S1). Unlike intentional introductions, the spread of hitch-hikers is usually unintentional, caused mainly by poor monitoring and the presence of suitable water environments.

Non-native escapees can also destroy the genetic integrity of native species through genetic pollution, which can reduce genetic diversity, alter population structure and cause species extinctions in native ecosystems. In China, about 10 NAS have the potential to cause genetic pollution (Table S1), and at least four species, including the Pacific abalone *Haliotis discus discus* and three carp species (*Cyprinus* spp.), have been confirmed to infiltrate their genetic materials into native gene pools (Li, Dong, Li, & Wang, 2007). Risks of genetic pollution depend on whether there are kin species with NAS escapees in water bodies. Because genetic pollution is not readily observed by the human eye, its evolutionary and ecological consequences can be underestimated. The ecological risks of genetic pollution may, however, exceed those of direct competition and predation. A typical case concerning these risks to the endangered Chinese sturgeon *Acipenser sinensis* (Figure 2) in the Yangtze River by the escape of non-native sturgeons is illustrated in Appendix S1.

FIGURE 2 The Chinese sturgeon. Credit: Ping Zhuang

4 | RECOMMENDATIONS FOR IMPROVED MANAGEMENT

Considering current trends of NAS expansion and escapes, we expect that global aquatic biosecurity and aquaculture sustainability will face intense pressure. Regulatory inefficiencies, however, exist in most countries (FAO, 2016). China is not a special case, because the irresponsible use of NAS to achieve short-term profits has been documented world-wide and especially in developing countries that rely heavily on aquaculture (e.g. Brazil and several other South American countries; Casal, 2006; Lima-Junior et al., 2018). More effective management measures, therefore, are needed in China and other developing countries. We propose here five ways to improve aquaculture management in order to reduce NAS escapes and their invasion risks.

First, NAS management must be integrated into the national system of preventing and controlling invasive species. China and many developing countries are signatories of the Convention on Biological Diversity and must, therefore, engage in dealing comprehensively with the introduction, control and eradication of NAS, which requires the passing of new laws (Pelicice et al., 2014). In this respect, several developed countries (e.g. UK and New Zealand) and international organizations have taken actions (see Table S2), but most developing countries have not. In some countries, such as Brazil, policy-making is even moving in the opposite direction (i.e. the farming of

NAS is being encouraged by decrees; Pelicice et al., 2014). In China, the 15 laws and regulations (see Table S3) concerning the management of non-native species focus mainly on terrestrial species but largely neglect NAS. Moreover, an integrated law dealing specifically with non-native species is still lacking in most developing countries. In this respect, New Zealand's *Hazardous Substances and New Organisms Act* (1996) provides a useful reference for other countries. In July 2019, the National People's Congress (NPC) of China discussed the legislation of *Biosafety Law*, but this law mainly concerns rational uses of biotechnologies and genetic resources and does not consider invasive species. Although China is currently also discussing the development of national law of biological invasion, when it will be issued and whether it will consider NAS remains unclear. We urge that a comprehensive law that considers all non-native species be launched soon in China and other developing countries. This law should concern prevention and early warning, risk assessment, detection and monitoring, control and emergency response.

Second, an effective agency should be established for NAS governance in each developing country, because the responsibility for NAS management in most countries is currently fragmented among agencies (FAO, 2016). In this regard, EU countries provide a model that developing countries can follow; within each EU country, a national lead organization is being established to coordinate NAS management between agencies (FAO, 2016). Considering China's existing administrative system, an effective cross-department agency under four new departments (the Ministry of Ecology and Environment, the Ministry of Natural Resources, the Ministry of Agriculture and Rural Affairs and the General Administration of Customs; see Table S4) is needed to coordinate the management of transferred species including NAS. This agency would be responsible for NAS risk assessment, monitoring and control. Sound management should be executed as indicated by the *FAO Code of Conduct for Responsible Fisheries* and *Code of Practice on the Introductions and Transfers of Marine Organisms* in China and other developing countries. Such management must consider various introduction activities or related events (i.e. international introductions, domestic transfers and intentional releases; Lin et al., 2015). Based on the precautionary principle, a rigorous risk assessment protocol should be performed in which a new NAS is considered potentially harmful and therefore prohibited unless proven otherwise. The domestic spread of existing NAS must be minimized, and their intentional releases must be forbidden. The use of NAS can only be permitted under secure farming conditions (e.g., enclosed systems, infertile culture). All NAS should be strictly monitored to prevent escapes and pathogen releases; in case of NAS escapes/releases, containment and eradication actions should be initiated immediately. Moreover, a national or even transnational network should be developed to monitor harmful invaders across shared regions.

Third, national standards/planning should be developed for the construction and operation of aquaculture facilities. In China and other developing countries, aquaculture is now dominated by small- and medium-scale farmers whose facilities cannot withstand large floods or severe storms (FAO, 2016). With climate change, this situation would increase the chances of NAS escapes (Kernan, 2015). To reduce NAS escapes, the development of national standards/planning should focus on (a) aquaculture zoning to minimize risks (for new aquaculture), and relocation to less-exposed areas (existing farms); (b) reducing shallow-pond aquaculture and preventing illegal aquaculture; (c) strengthening farming systems, including the use of improved holding structures (e.g. sturdier cages, depth-adjustable cages, deeper ponds) and management practices (FAO, 2016). To minimize the negative effects of NAS that escape from facilities, fishery agencies should develop emergency plans and should train farmers about how to dispose of NAS escapees (e.g. mobilizing local farmers to rapidly recapture and kill escapees).

Fourth, the farming of local/regional species should be encouraged in developing countries, i.e., increases in aquaculture production should not rely on NAS. Many developing countries have local/regional aquatic species with commercial value that should be preferentially developed for aquaculture. Total fishery production in the small country of Myanmar, for example, is similar to that in Brazil but is totally based on local/regional species even though fish diversity in Myanmar is low (Casal, 2006). Myanmar provides a good example for megadiverse developing countries. We recognize that intensive aquaculture, whether with local/regional species or with NAS, can create environmental problems, but these problems can be solved by proper management (Gichuki, Kodituwakku, Nguyen-Khoa, & Hoanh, 2009). Regarding China, there are >100 local/regional fish species with high economic value, but only about 10 species are commonly used for aquaculture (Lou, 2000). China's government, therefore, should develop policies to encourage the use of local/regional species for aquaculture in situ. We note, however, that because the genotypes of local/regional species may differ among isolated habitats, the use of these genotypes in different habitats/regions within a country, especially a country with a large territory like China, also requires rigorous risk assessment. Relevant policies should be based on basic ecological/fishery data, such as the status of wild stocks and the carrying capacity of ecosystems (Pelicice et al., 2014), and should include safe confinement, waste treatment and technical support, industrial chain, etc..

Finally, integrated research and education regarding the prevention and control of NAS is desperately needed. Globally, aquaculture studies have largely focused on technology and disease control even though the potential ecological impacts of most farmed NAS are unknown (FAO, 2019). A metacoupled human and natural systems approach (Liu, 2017) can help provide a holistic understanding of the socioeconomic and ecological risks associated with the use of NAS within a focal area, adjacent areas and distant areas. We need more new tools (e.g. remote sensing, artificial intelligence and novel molecular tools) to rapidly monitor/detect NAS escapees and their 'hitch-hikers'. We need more cost-effective ways to contain NAS (e.g. low-cost closed systems). We also need more information about how to quantify escapes and to dispose of escapees. It is also important that ecological education should be mandatory for the aquacultural community, and the knowledge gained from research should be rapidly transferred to aquaculture managers and the public. 'Translational scientists', who are undervalued in developing countries, are especially needed to increase the understanding of non-specialists about NAS invasion and conservation issues (Briske, 2012). Increasing public understanding is important because informed public can exert pressure on the authorities to make correct policies.

In conclusion, NAS escapes have already had adverse ecological effects in China and other developing countries. The risk of NAS escapes is not adequately recognized by current conservation policies, and unless action is promptly taken, NAS escapes will continue to degrade aquatic ecosystems world-wide. To conserve biodiversity and to support sustainable aquaculture, the governments and citizens of developing countries should now recognize and solve the problems resulting from NAS farming and escapes. In addition to developing legislation, each country should establish an agency as well as national and transnational networks to deal with risk assessment, prevention, monitoring and control of NAS escapes. Moreover, integrated research and knowledge transfer should be strengthened. Given that China has been the world's largest producer of aquaculture, China's efforts can help create a model for other developing countries that will contribute greatly to the biosecurity and sustainability of global aquaculture.

ACKNOWLEDGEMENTS

We thank Prof. Bruce Jaffee, Dr. Sarah Knutie and three anonymous reviewers for thoughtful comments and suggestions. Funding was provided by the National Key Research and Development Program of China (2017YFC1200100, 2018YFC1406402), the National Natural Science Foundation of China (31670544) and the Project of Science and Technology Commission of Shanghai (18DZ1206507).

AUTHORS' CONTRIBUTIONS

R.-T.J., X.L. and B.L. conceived the manuscript and led the writing. All authors contributed to the draft and gave approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository https://doi.org/10.5061/dryad.cjsxksn1h (Ju et al., 2019).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Ju R-T, Li X, Jiang J-J, et al. Emerging risks of non-native species escapes from aquaculture: Call for policy improvements in China and other developing countries. *J Appl Ecol*. 2019;00:1–6. https://doi.org/10.1111/1365-2664.13521

Supporting information

Appendix S1 A typical case: the iconic Chinese sturgeon is threatened by escaping non-native sturgeons

Sturgeon farming is expanding worldwide due to the overexploitation of wild stocks. In China, the main farmed species are non-native species or their hybrids (Shen, Shi, Zou, Zhou, & Wei, 2014) that can invade and establish in natural ecosystems if they escape from farming facilities. Unfortunately, escapes are frequent due to poor management and frequent extreme weather events. A typical case occurred in July 2016, when floods hit the middle reaches of the Yangtze River. Flood discharges caused the escape of 9800 tonnes of five non-native sturgeon species (the Amur sturgeon *Acipenser schrenckii*, the Siberian sturgeon *A. baerii*, the Kaluga sturgeon *H. dauricus*, the Russian sturgeon *A. gueldenstaedti*, and the American paddlefish *P. spathula*) and some of their hybrids from farming facilities in the Qingjiang Reservoir in Hubei Province (Wu, 2016; Gao et al., 2017). The escapees have now spread into almost all of the lower streams (>1000 km) including the Yangtze River estuary, Dongting Lake, and Poyang Lake (Wu, 2016). The escapees greatly threaten native biodiversity, and the risk is especially high for the endangered Chinese sturgeon *A. sinensis*.

The Chinese sturgeon, one of the largest anadromous fish, spawns only in the downstream waters of the Gezhouba Mega-Dam in the Yangtze River. It is extinct in Korea and throughout the rest of its pre-Anthropocene range, such that all individuals of this species are in China. The species has an independent history of >1 billion years and is therefore regarded as an ideal species for studies of climate change and fish evolution (Zhuang et al., 2016). China’s government has assigned the Chinese sturgeon the highest priority for conservation, and all commercial captures have been prohibited since 1983. Because of damming and other human disturbances in the Yangtze River basin, however, the Chinese sturgeon population has declined to <100 individuals (Zhuang et al., 2016). The species is considered critically endangered by IUCN (IUCN, 2014) and is listed in Appendix II of the *Convention on International Trade in Endangered Species of Wild Fauna and Flora* (CITES) (CITES, 2017).

The Yangtze River currently contains larger numbers of escaping non-native sturgeon than Chinese sturgeon. Because the non-native and Chinese sturgeons have similar ecological niches (Gao et al., 2017), asymmetric competition can reduce the availability of spawning grounds and other resources for the Chinese sturgeon, especially in the Yangtze estuary. In addition, most escaping non-native sturgeons are congeneric species with the Chinese sturgeon, and hybridization can lead to genetic pollution and destruction of the genetic integrity of the Chinese sturgeon. Although China's fishery administration is trying to remove the escapees from the invaded waters (MAC, 2016), this activity is unlikely to be effective because aquatic invaders are very difficult to eliminate. Furthermore, the removal activity itself can incidentally damage the Chinese sturgeon. In addition to the Chinese sturgeon, about 370 native fish species inhabit the Yangtze River, among which >30 species are rare and endemic to China (Xie, 2017). Because sturgeons are carnivorous, the non-native escapees also threaten these native species. The fishery sector is still seeking more effective approaches to dealing with this serious problem.

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Table S1 Established non-native aquatic species and their potential effects in China's aquaculture. Potential effects are shown as genetic pollution (GP), carrying harmful organisms (CH), competing with native species for space and/or food (CN), preying on native species (PN), altering habitat structure (AH), and polluting the environment (PE).

No.	Type	Order	Family	Species	Origin	Potential effect	Major reference
1	Echinodermata	Echinoida	Strongylocentrotidae	*Strongylocentrotus intermedius*	Japan	GP, CN	Chang, Wang, Song, Su, & Wang (2000)
2	Reptilia	Anura	Ranidae	*Rana catesbeiana*	North America	PN	Li & Xie (2004)
3	Testudines	Testudoformes	Emydidae	*Trachemys scripta*	America	CN, PN, CH	Li et al. (2005)
4	Crustacea	Decapoda	Cambaridae	*Procambarus clarkii*	USA, Central and South America	CN, PN, AH	Li, Dong, Li, & Wang (2007)
5			Varunidae	*Eriocheir sinensis*	North to Liaoning, south to Fujian, west to Hubei	PN, AH	Ren & Shao (2004)
6			Portunidae	*Scylla serrata*	South China	PN	Liu, Yang, & Zhang (1995)
7	Algae	Desmarestiales	Desmarestiaceae	*Desmarestia ligulata*	Japan	PE	Shao & Li (2000)
8		Laminariales	Alariaceae	*Undaria pinnatifida*	Japan, Korea	CN, CH	Liang & Wang (2001)
9	Mollusca	Ostreida	Ostreidae	*Crassostrea gigas*	Japan, Australia	PE	Guo (2009); Sun et al. (2010)
10		Mytilida	Mytilidae	*Mytilus galloprovincialis*	Mediterranean, Black and Adriatic Seas	PE	Li et al. (2007)
11		Stylommatophora	Achatinidae	*Achatina fulica*	Africa	PN, CH	Li et al. (2007)
12		Archaeogastropoda	Haliotidae	*Haliotis discus discus*	Japan	GP	Zhang, Que, Liu, & Xu (2004)
13		Mesogastropoda	Ampullariidae	*Pomacea canaliculata*	South America	PN, CH	Li et al. (2007)
14	Fish	Acipenseriformes	Polyodontidae	*Polyodon spathula*	North America	Unknown	Ba & Chen (2012)
15		Anguilliformes	Anguillidae	*Anguilla anguilla*	Europe	CN, GP	Li et al. (2007)
16				*Anguilla rostrata*	North America	CN, GP	Li et al. (2007)
17		Cypriniformes	Cyprinidae	*Carassius cuvieri*	Asia	CN	Chen (1994)
18				*Carassius auratus gibelio*	Heilongjiang and Liaohe Rivers	CN	Wang, Wu, Dou, & Huang (2009)

19			*Cirrhinus mrigala*	Asia	PN	Li et al. (2007)
20			*Labeo rohita*	Asia	CN	Li et al. (2007)
21			*Tinca tinca*	Europe	CN	Xu & Qiang (2011)
22			*Cyprinus carpio*	Europe	CN, GP	Ren et al. (2002)
23			*Cyprinus carpio* var. *mirror*	Ukraine	GP	Li et al. (2007)
24			*Cyprinus carpio* var. *specularis*	German	GP	Li et al. (2007)
25			*Abramis brama*	Europe	Unknown	Wang (1995)
26			*Ctenopharyngodon idellus*	Yangtze and Peal Rivers	CN	Wang et al. (2009)
27			*Hypophthalmichthys molitrix*	Southeast China	CN	Wang et al. (2009)
28			*Hypophthalmichthys nobilis*	Northeast and North China	CN	Wang et al. (2009)
29			*Mylopharyngodon piceus*	Yangtze and Peal Rivers	CN	Wang et al. (2009)
30		Catostomidae	*Ictiobus cyprinellus*	North America	CN	Li et al. (2007)
31	Characiformes	Curimatidae	*Prochilodus lineatus*	South America	Unknown	Zhu & Lan (2012)
32		Characidae	*Piaractus brachypomus*	South America	CN	Li et al. (2007)
33			*Pygocentrus nattereri*	South America	PN	Li et al. (2007)
34	Siluriformes	Clariidae	*Clarias batrachus*	Asia	CN, PN	Li et al. (2007)
35			*Clarias gariepinus*	Africa	CN	Li et al. (2007)
36		Ictaluridae	*Ictalurus punctatus*	North America	CN	Ba & Chen (2012)
37			*Ictalurus furcatus*	North America	Unknown	Yu et al. (2011)
38		Pangasiidae	*Pangasianodon hypophthalmus*	Asia	Unknown	Li, Zhang, Yuan, Feng, Zhang, & Yang (2008)
39		Siluridae	*Silurus glanis*	Europe	PN	Chen, Guo, & Wu (2010a)
40	Salmoniformes	Salmonidae	*Oncorhynchus kisutch*	North America	CN, GP	Xu & Qiang (2011)
41			*Oncorhynchus mykiss*	North America	CN, GP, PN	Xu & Qiang (2011)
42			*Salmo trutta*	Europe	Unknown	Hao, Chen, & Cai (2006)
43			*Salmo salar*	North America	CN, CH	Xu & Qiang (2011)
44			*Salvelinus fontinalis*	North America	PN	Tang & He (2013)
45			*Coregonus muksun*	Europe	Unknown	Tang, Chen, & Ding (2013)
46			*Coregonus peled*	Europe	Unknown	Tang et al. (2013)

47			*Coregonus nasus*	Europe	Unknown	Tang et al. (2013)
48		Salangidae	*Neosalanx taihuensis*	Lake Tai	CN	Wang et al. (2009)
49			*Protosalanx chinensis*	Lake Tai	CN	Wang et al. (2009)
50	Osmeriformes	Osmeridae	*Hypomesus olidus*	Heilongjiang and Tumenjiang Rivers	CN	Li et al. (2008)
51			*Hypomesus nipponensis*	Asia	Unknown	Tang et al. (2013)
52	Perciformes	Ceutrarchidae	*Micropterus salmoides*	North America	PN	Li et al. (2007)
53			*Lepomis macrochirus*	North America	CN	Xu & Qiang (2011)
54			*Lepomis megalotis*	North America	Unknown	Chen et al. (2010a)
55			*Lepomis auritus*	North America	Unknown	Chen et al. (2010a)
56			*Pomoxis nigromaculatus*	North America	Unknown	Chen et al. (2010a)
57		Centropomidae	*Lates calcarifer*	Asia	CN, PN	Xu & Qiang (2011)
58		Cichlidae	*Oreochromis aureus*	Africa	CN, GP	Xu & Qiang (2011)
59			*Oreochromis mossambicus*	Africa	PN	Ba & Chen (2012)
60			*Oreochromis niloticus*	Africa	CN	Xu & Qiang (2011)
61			*Sarotherodon galilaeus*	Africa	Unknown	Yu et al. (2011)
62			*Tilapia zillii*	Africa	CN	Deng, Zhang, Zhao, Zhou, & Zhang (2013)
63		Eleotridae	*Oxyeleotris marmorata*	Asia	Unknown	Chen, Shen, Meng, & Qu (2010b)
64		Moronidae	*Morone saxatilis*	North America	CN, PN	Li et al. (2007)
65		Percidae	*Sander lucioperca*	Europe	PN	Ren et al. (2002)
66			*Perca fluviatilis*	Asia	PN	Xu & Qiang (2011)
67	Tetraodontiformes	Tetraodontidae	*Takifugu rubripes*	Asia	Unknown	Chen et al. (2010a)
68	Anabantiformes	Channidae	*Channa striatus*	Southeast Asia	PN	Li (1992)

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Table S2 Major international conventions and the acts/regulations/statutory instruments of some developed countries related to non-native aquatic species.

Type	List
International conventions	● Convention on Biological Diversity (1992) (https://www.cbd.int/)
	● Convention on International Trade in Endangered Species of Wild Fauna and Flora (1975) (https://www.cites.org/)
	● United Nations Convention on the Law of the Sea (1982) (https://www.un.org/)
	● Convention on the Law of the Non-navigational Uses of International Watercourses (1997) (http://legal.un.org/)
	● Convention on Wetlands of International Importance Especially as Waterfowl Habitat (1982) (https://www.ramsar.org/)
	● International Convention for the Control and Management of Ships' Ballast Water and Sediments (2004) (http://www.imo.org/)
Acts/regulations/statutory instruments of some developed countries	● Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species (2014), the EU (http://www.legislation.gov.uk/)
	● Council Regulation (EC) No 708/2007 of 11 June 2007 concerning use of alien and locally absent species in aquaculture (2007), the EU (http://www.legislation.gov.uk/)
	● Import of Live Fish (England and Wales) Act (1980), the EU (http://www.legislation.gov.uk/)
	● The Invasive Alien Species (Enforcement and Permitting) Order (2019), the United Kingdom (http://www.legislation.gov.uk/)
	● The Animal Health, Alien Species in Aquaculture and Invasive Non-native Species (Amendment) (EU Exit) Regulations (2019), the United Kingdom (http://www.legislation.gov.uk/)
	● The Aquatic Animal Health and Alien Species in Aquaculture (Amendment etc.) (EU Exit) Regulations (2019), the United Kingdom (http://www.legislation.gov.uk/)

- The Alien and Locally Absent Species in Aquaculture (England and Wales) Regulations (2011), the United Kingdom (http://www.legislation.gov.uk/)
- The Fisheries and Aquaculture Structures (Grants) (England) (Amendment) Regulations (2008), the United Kingdom (http://www.legislation.gov.uk/)
- Nonindigenous Aquatic Nuisance Prevention and Control Act (1990), The United States (https://www.law.cornell.edu/)
- National Invasive Species Act (1996), The United States (https://www.law.cornell.edu/)
- Executive Order 13112 (1999), The United States (https://www.archives.gov/)
- Fisheries Act (1985), Canada (https://laws-lois.justice.gc.ca/)
- Aquatic Invasive Species Regulations (2015), Canada (https://laws-lois.justice.gc.ca/)
- Ontario Fishery Regulations (2007), Canada (https://laws-lois.justice.gc.ca/)
- Invasive Alien Species Act (2004), Japan (http://www.env.go.jp/en/)
- Biosecurity Act (1993), New Zealand (http://www.biosecurity.govt.nz/)
- Hazardous Substances and New Organisms Act (1996), New Zealand (http://www.mfe.govt.nz/)

Table S3 Major laws and administrative regulations concerning the management of non-native species in China. PRC: the People's Republic of China. NPC: the National People's Congress, PRC. SC: the State Council, PRC. For each law or regulation, the first promulgating date and the newest amending date are shown in brackets.

Name	**Issuing authority**	**Download**
Agriculture Law of PRC (1993, 2012)	NPC	http://english.agri.gov.cn/governmentaffairs/lr/comp/201304/t20130423_19504.htm
Fisheries Law of PRC (1986, 2013)	NPC	http://english.agri.gov.cn/governmentaffairs/lr/201810/t20181022_296061.htm
Environmental Protection Law of PRC (1989, 2014)	NPC	http://language.chinadaily.com.cn/trans/2014-05/20/content_17522868.htm
Forest Law of PRC (1984, 2009)	NPC	http://english.agri.gov.cn/governmentaffairs/lr/ep/201301/t20130115_8133.htm
Law of PRC on the Entry and Exit Animals and Plants Quarantine (1991, 2009)	NPC	http://english.agri.gov.cn/governmentaffairs/lr/ie/201301/t20130115_8137.htm
Frontier Health and Quarantine Law of PRC (1986, 2018)	NPC	http://english.gov.cn/archive/laws_regulations/2014/08/23/content_281474983042126.htm
Law of PRC on Animal Epidemic Prevention (1997, 2015)	NPC	http://english.gov.cn/archive/laws_regulations/2014/08/23/content_281474983042389.htm
Marine Environment Protection Law of PRC (1982, 2017)	NPC	http://english.agri.gov.cn/governmentaffairs/lr/ep/201305/t20130509_19614.htm

Law of PRC on the Protection of Wildlife (1998, 2018)	NPC	http://english.agri.gov.cn/governmentaffairs/lr/ep/201304/t20130423_19507.htm
Regulations on Plant Quarantine (1983, 2017)	SC	http://www.gov.cn/flfg/2005-08/06/content_21028.htm
Regulations for the Implementation of Forestry Law of the PRC	SC	http://www.gov.cn/flfg/2005-09/27/content_70635.htm
Regulations for the Implementation of the Law of PRC on the Entry and Exit Animal and Plant Quarantine (1996)	SC	http://english.agri.gov.cn/governmentaffairs/lr/ie/201305/t20130509_19615.htm
Regulations on Administration of Agricultural Genetically Modified Organisms Safety (2001, 2017)	SC	http://english.agri.gov.cn/governmentaffairs/lr/st/201301/t20130115_8106.htm
Regulations for the Implementation of the PRC on the Protection of Terrestrial Wildlife (1992, 2016)	SC	http://english.agri.gov.cn/governmentaffairs/lr/ep/201301/t20130115_8090.htm
Regulations for the Implementation of PRC on the Protection of Aquatic Wildlife (1993, 2013)	SC	http://www.gov.cn/gongbao/content/2014/content_2695332.htm

Table S4 Major departments related to the management of non-native species in China. MEE: Ministry of Ecology and Environment, the People's Republic of China (PRC). MNR: Ministry of Natural Resources, PRC. MARA: Ministry of Agriculture and Rural Affairs, PRC. GAC: General Administration of Customs, PRC.

Ministry	**Responsibility**	**Data sources**
MEE	● Management of non-native species in natural ecosystems. ● Conservation of biological diversity.	http://www.mee.gov.cn/
MNR	● Conservation of marine ecosystem, including the management of non-native species in marine ecosystem. ● Risk assessment, monitoring, precaution, and control of non-native species in forest ecosystems.	http://www.bjdc.mlr.gov.cn/ http://www.forestry.gov.cn/
MARA	● Coordinate national management of non-native species. ● Risk assessment, monitoring, precaution, control, and information release concerning non-native species in agricultural ecosystems.	http://www.moa.gov.cn/
GAC	● Inspection, quarantine, and supervision of entry-exit animals and plants as well as animal and plant products. ● Organize and implement risk analysis and emergency precautions for non-native species.	http://www.customs.gov.cn/

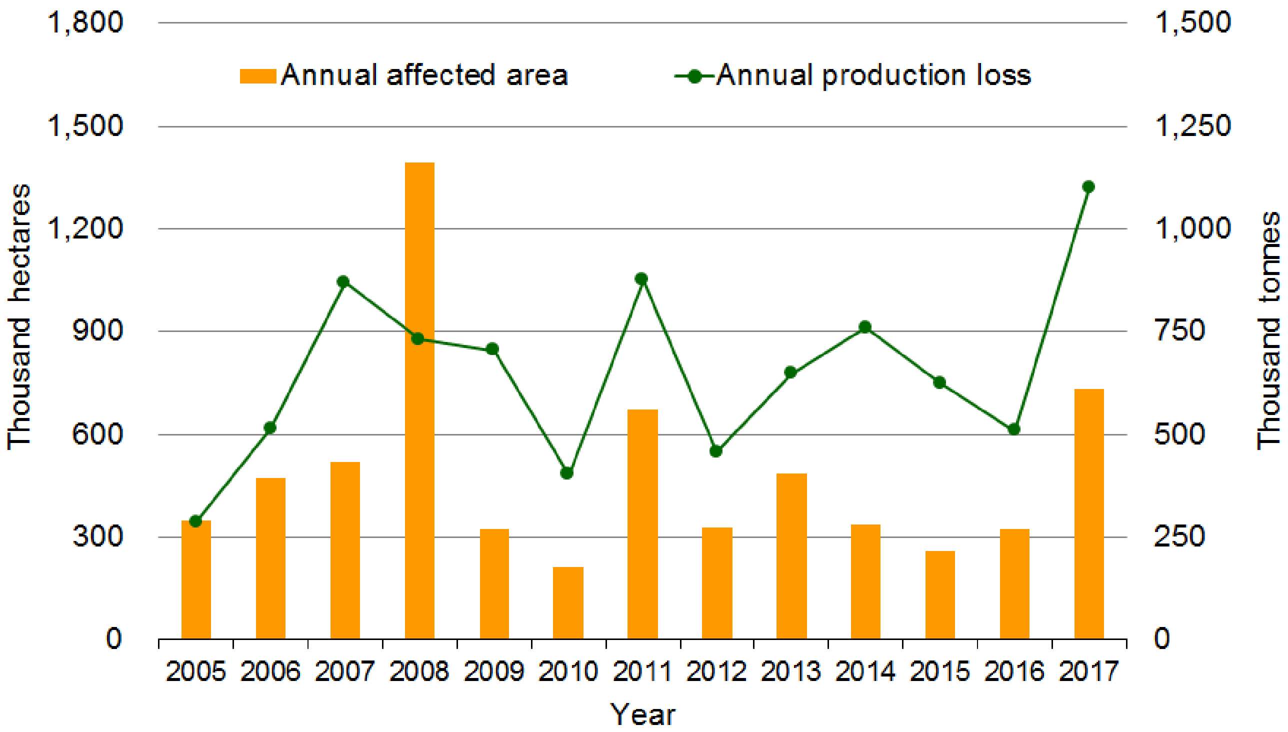

Figure S1 Annual affected area and production loss of China's aquaculture by typhoon and flood (2005–2017). An extreme flood occurred in 2008. Data from FBMAC (2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017).

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